Control of a Manual Transmission in an Electric Land Speed Vehicle

A Thesis submitted for partial fulfillment
of requirements for graduation with distinction
for the degree of Bachelor of Science
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Abstract

The Buckeye Bullet is a land speed vehicle which currently holds the record for the fastest electric vehicle. In order to improve upon the success of the Buckeye Bullet, the Buckeye Bullet 2 is being designed to reduce losses and improve upon safety of its predecessor. To this end, the development of a control method which would take into account many vehicle parameters in order to automatically control the Buckeye Bullet 2's sequential transmission is being investigated and developed. In addition, due to the nature of land speed vehicles and the inherent risk involved, it is very important that the driver be as focused as possible, and that the vehicle be very reliable. This research project investigates through modeling the effect that a control system would have on the existing Buckeye Bullet, and develops such a control system to be implemented onto the Buckeye Bullet 2.

Chapter 1

Introduction

1.1 Motivation

In recent years, a substantial interest in alternate energy vehicles has been the focus of public attention. The finite amounts of energy resources in the world are becoming more publicly known as people are more conscious of their energy usage. Part of the interest has focused on understanding ways to efficiently use these resources.

In the vehicle test arena of land speed racing, automobiles are pushed to their physical limits of power and speed in an attempt to break the record in their vehicle's category. The Ohio State University's (OSU) Buckeye Bullet team is involved with building an electric land speed vehicle that challenges the records for electric cars. In the Fall of 2004, the team began developing a new vehicle that would challenge the records, with a fuel cell powered vehicle. Through automating the manual transmission that will be in this new vehicle, this research project will seek to understand whether or not such an automation would be advantageous to improving the efficiency and safety of this new land speed car.

1.2 Land Speed Racing

The people involved in land speed racing represent a very unique community. The environment in which the racing takes place is very harsh on both people and equipment. This type of racing takes up large amounts of land, and that land must be flat enough such that automobile racing can take place. In the United States, there are primarily two locations where organized land speed record events are regularly held. They are the Blackrock Desert in California, and the Bonneville Salt Flats in Utah. For wheel-driven vehicles, the Blackrock Desert does not provide enough traction for records to be possible, so most wheel-driven records are set at the Bonneville Salt Flats.

There are two ways in which records may be set, depending on whether they are International Records or National Records. For a National Record, the racing course is seven miles in length. The vehicle is given two miles in which to accelerate, and then three miles in which the average speed over each of the miles is recorded, and then two miles to stop the vehicle, as shown in Figure

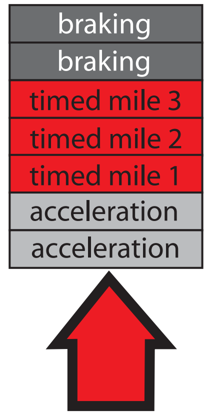

Figure 1.1: Diagram of a Land Speed Record Run

Figure 1.2: The Buckeye Bullet 1

1.1. For a record to be set the vehicle must exceed the existing record in its first run, where it is then sent to impound where at least four hours of basic maintenance may be made on it. Then it makes a second run, in the same manner as the first, and if the average of the top speeds of the two runs exceeds the existing record, then a new record is made. For international records, the same manner of creating a new record is done, however, the vehicle is given as much space to get up to speed as the course will allow, and it must turn around and make a second run, in the opposite direction within an hour of its first run.

1.2.1 The Buckeye Bullet

In the early 1990s, Ohio State University participated in a collegiate automotive series known as the Formula Lightning program. As that program began to dissolve, a new project was developed by the students which would challenge the electric land speed record. The result of this project was the Buckeye Bullet, a 32-foot, 2-ton streamliner, has a top recorded speed of 321 miles per hour and currently holds the national and international land speed records for the unlimited weight class (greater than 1000kg) of electric vehicles, and is shown in Figure 1.2. One of the challenges of such a unique project is the difficult in acquiring meaningful data. The vehicle was transported to the to the Bonneville Salt Flats a maximum of two times per year, and makes only a handful of high speed runs each time it is on the flats.

Figure 1.3: The Buckeye Bullet 2

1.2.2 The Buckeye Bullet 2

The Buckeye Bullet 2 is the successor to the Buckeye Bullet. After deciding to retire the Bullet in 2005, the team began working on developing a new vehicle that would incorporate all of the lessons that had been learned through the development of the original Buckeye Bullet. Using a more advanced understanding about high speed aerodynamics, safety, chassis, and many other design elements, the team seeks to design a car that improves upon the designs of its predecessor through incorporating the knowledge gained both in the design process as well as in practice runs on the Salt Flats.

1.2.3 Roger Schroer: Buckeye Bullet Driver

One of the objectives of the work described in this thesis is to automate processes previously assigned to the driver. For example, the anti-lock brake system was implemented to do a better job than a driver could do in pumping their brakes in the event of losing traction. With regards to shifting, the situation is analogous; the shifting was previously done by the driver, and now it is desired to automate and control it. Greater performance would result with automation of the control, resulting in better performance from the system.

In order to understand the system that was utilized previously, it is important to understand the driver. Roger Schroer volunteers his time as driver for the Buckeye Bullet team, but is employed professionally at the Transportation Research Center (TRC) as a driver trainer for employees at TRC as well as the nearby Honda facilities, which include both research and manufacturing facilities. He is a very experienced driver, who understands very well the way to properly drive a vehicle, and the practical limits of vehicles. Therefore, automation of some systems will allow him to better focus on the driving of the vehicle.

1.3 Transmission System in the Buckeye Bullet

In the development of the Buckeye Bullet, much of the focus was on the mechanical systems of the vehicle. Since the concept of land speed racing was fairly new to the team, much of the focus was put into making sure that the car could actually make a run at the record, and automation was not considered, as it would further complicate the vehicle, and thus jeopardize its reliability.

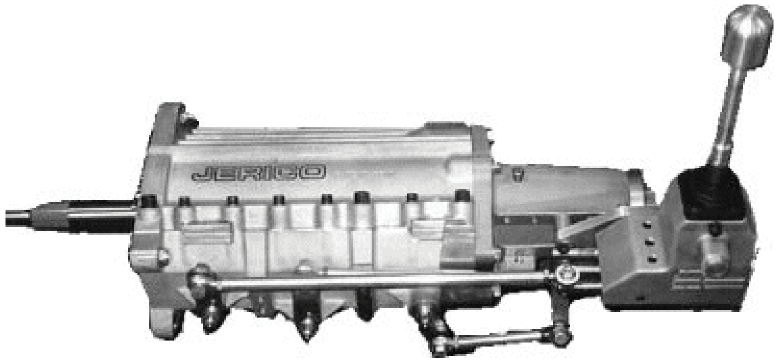

Figure 1.4: Jerico 5 Speed Transmission

Figure 1.5: The Buckeye Bullet Jerico 5 Speed Transmission

The transmission was a standard 5-speed Jerico transmission, similar to the type that is used in dragsters. It is shown in Figure 1.4. It is capable of 600 horsepower, and uses a sequential shifter to change gears. To use it, the driver has to manually apply the clutch, then either push or pull the shift lever in order to change gears. The shift lever used three push-pull cables that would slam the dogrings into place to engage the gears. One obvious disadvantage of this system was that, having multiple push-pull cables, it was possible that a double gear engagement could occur. This was partly responsible for the long shift times, as the driver wanted to be very deliberate in making shifts, so as to not cause a double gear engagement. The transmission that was in the Buckeye Bullet is shown in Figure 1.5

1.4 Buckeye Bullet 2 Objectives

In April of 2005, a design summit was held at the Center for Automotive Research (CAR) on campus of The Ohio State University. The purpose of the summit was to discuss the development of the Buckeye Bullet 2, and included current and former team members, partners from industry, faculty, and experienced land speed racers.

One important aspect that was discussed was reducing the losses that occurred during a run down the track. The shape would be designed to be more streamlined to reduce the aerodynamic drag. Driveline components would be selected with high efficiency as a top criteria. Reducing shift times was also discussed as a priority. During the time to make a shift, all of the losses in the vehicle are working against the car for that short period, such that there is no forward force being applied to the car. The ability to reduce the shift time period would be able to reduce the losses that exist during the shift time, and ultimately improve the top speed.

1.4.1 Control Objectives

Now that the Buckeye Bullet team has a significant amount of experience with land speed racing, implementing more complex strategies that will improve performance is a desire of the team. When the Buckeye Bullet was built, one of the main objectives was to eliminate complexity for both safety as well as ease of repair while out on the salt flats. With experience in the racing environment, one of the areas of control that is being explored is to improve the performance, decrease driver distraction, and improve reliability through automatic shifting of the vehicle's sequential transmission.

Next to safety, the next highest optimization priority is in maximization of vehicle exit speed. This implies that all efforts should be directed toward overcoming inertial forces. To do this, any other losses need to be reduced. This includes losses in electrical and mechanical components, and improving aerodynamic performance to reduce loss due to drag. Reducing the effects of these losses can be achieved by reduction of the shift time, which lessens the time that these forces have to act against the forward motion of the vehicle.

1.5 Thesis Objectives

The purpose of this thesis comprises the following objectives:

- Simulate the effects of a shortened shift on the existing Buckeye Bullet 1 model, which has been shown to compare to collected run data. Determine the energy savings and increases in exit speed due to the shorter shift.

- Using the Buckeye Bullet 2 model, optimize through simulation a single shift point to maximize vehicle exit speed.

- Develop and design the shifting control scheme that will maximize the output power on the Buckeye Bullet 2, and best meet the control objectives.

- Test the control scheme in the Buckeye Bullet 2 dynamics model

The transmission shifting controller for the Buckeye Bullet 2, including the control scheme and implementation on a microcontroller, will be designed and analyzed as part of this thesis. The design work is being done in conjunction with the Buckeye Bullet team in the development of the Buckeye Bullet 2.

1.6 Thesis Summary

This thesis is set up in five chapters. Chapter one introduces the context of the topic, and provides the motivation for looking into performing this research. The second chapter gives a basic background into current transmission control methods, including those in motorsports, as well as information about the microcontroller and transmission that will be used in the vehicle. Chapter Three specifies the methodology about the design of the various components, and outlines how they will be implemented into the Buckeye Bullet 2. This includes all of the major components of the data acquisition and control network system. Chapter Four presents the results from the tests and experiments carried out from the information in Chapter Three. Finally, Chapter Five gives the conclusions and recommendations for future work in the communications and controls area of the Buckeye Bullet 2.

Chapter 2

Literature Review

2.1 Introduction

The concept of transmission control has been around for many years. To get a full understanding of the current state of the art, the work that has previously been done with transmissions was investigated. This includes previous research into land speed vehicles, automotive industry studies and current practices in the control of transmissions, and motorsports transmission control. Additionally, the hardware that will eventually be implemented on the Buckeye Bullet 2 will be studied to gain a better understanding of the physical capabilities and limitations that will be present in the vehicle.

2.2 Previous Buckeye Bullet Research

During the development of the Buckeye Bullet 1, extensive research was focused around understanding the operating conditions that face land speed vehicles. The team placed much of their study on the aerodynamics of the new vehicle, and documenting their design decisions [9]. One area that was addressed was the need to absorb the motor's energy during a shift. The clutch that was used by the Buckeye Bullet 1 is the same that will be used in the Buckeye Bullet 2. It is manufactured by Tilton, and is capable of absorbing 750 ft-lb of torque. Equation 2.1 shows the calculation of energy in the motor while it is spinning.

$$E = \frac{1}{2} I \omega^2 \tag{2.1}$$

In this equation, E represents energy, I is rotational inertia, and ω is the rotational speed. During the design of the Buckeye Bullet 1, the rotational inertia was found to be 0.265 m^2kg [9, p.53]. They found that for a 0.5 second shift, it would be required to have 120kW of resistors to absorb the motor's energy to bring it down from 10,000 RPM to 7,000 RPM [9, p. 55]. This can be seen in Figure 2.1. Electric motors have great power and torque over a wide range of speeds, but in the case of the Buckeye Bullet 1, a transmission can keep the motor spinning in the peak power range,

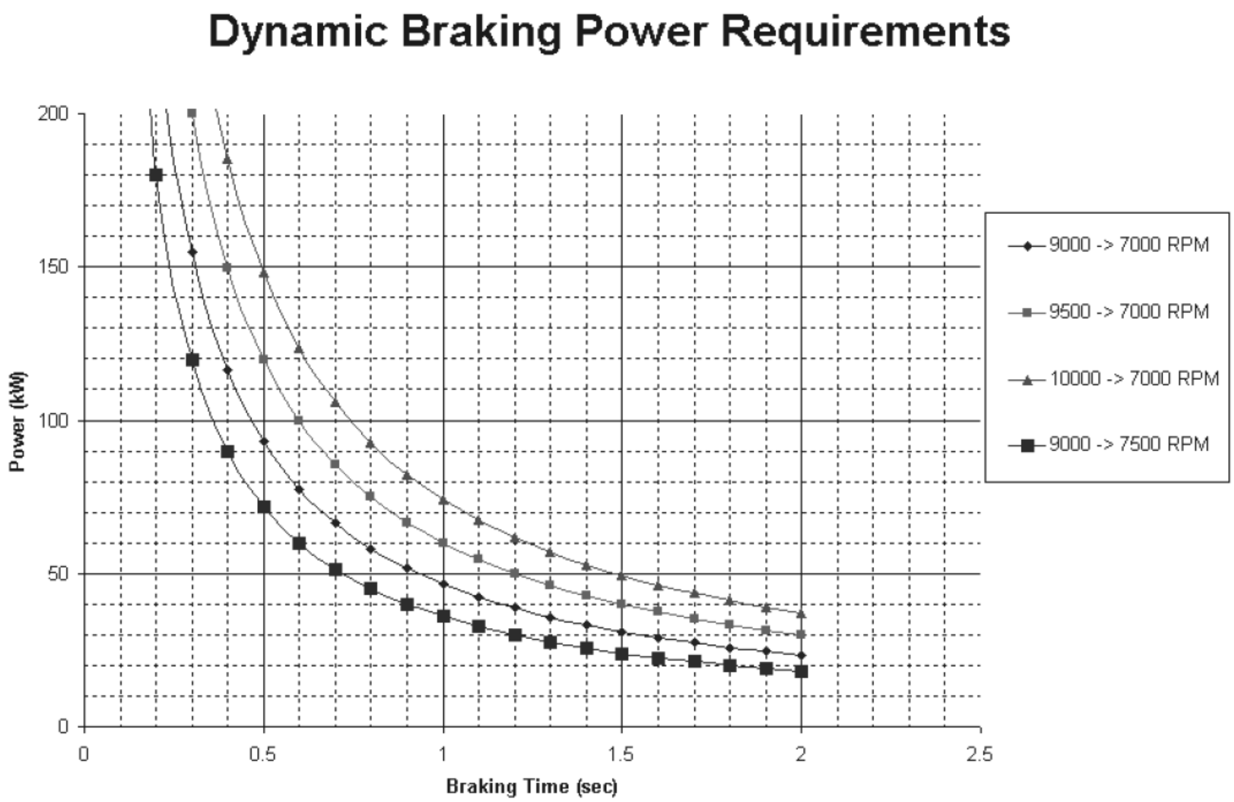

Figure 2.1: Braking Resistor Requirements [9, p.55]

and provide the maximum speed that the power supply will allow [9].

2.3 Transmission Control Schemes

When first developed, transmission control was done entirely by the driver's muscle power, manual shifting as we know it today. The driver served as the control interface between the engine and transmission. The decision to shift was accomplished by watching the tachometer, or simply shifting when it "felt right." While transmissions and transmission control have come a long way since then, most current systems still serve to mimic *when* that a driver would have shifted. Yet, many of the control schemes being used today in automatic transmissions do not give the same feel of control because they do not shift *how* the driver would have shifted [7]. While the style of shifting will be always be as quick as possible in the Buckeye Bullet 2, it is important to remember that, especially for an experienced racecar driver, the feel of the automatic shift point should still feel natural to the driver.

Some automatic transmission vehicles that are being manufactured today give the ability to use driver selected manual shifting, which essentially turns the vehicle from an automatic transmission to a "clutchless" manual transmission, where the driver selects when to shift, and the computer

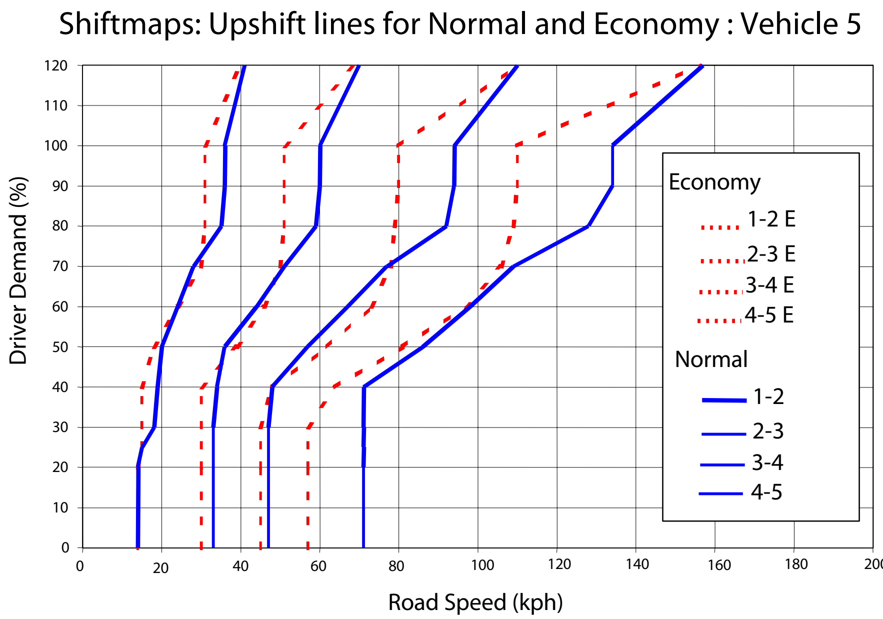

Figure 2.2: Sample Shift Map [12]

control manages the internal shift operation. A study conducted on several European cars equipped with this system found shift times on the order of 1.2 seconds, much larger than the speeds of around 0.8s that were seen with automatic transmissions [12]. This implies that the automatic transmissions that were tested performed better when in the fully automatic mode than compared to the "manual" mode.

This same study found that all of the vehicles utilized shift maps, which defined when the upshift should take place, based on driver input throttle demand and road speed. An example shift map that was found in this study is shown in Figure 2.2. This particular schedule was unique from the rest of the vehicles studied because it included a second map for increasing fuel economy.

There are a number of automated manual transmissions that have been developed in the past, or currently exist today:

- 1941 Chrysler M4/Vacamatic Transmission [10]
- Formula 1 Paddle Shift [11]
- Pro Stock Liberty [3]
- Citroens Sensodrive [5]
- Eaton AutoShift [6]

At first, it may appear that the automated manual transmission has already been developed in a number of applications, and no longer needs to be studied. But, closer inspection of each of these applications reveal that they are either inefficient or dated, or simply the wrong application. For example, the Formula 1 paddle shift system is optimized around a combustion engine, and the exact operation is kept as a trade secret.

2.4 Motorsports Transmission Control Schemes

Professional race teams recognize the importance of optimizing shift sequences, which has led to much research on this topic. However, this is an area where teams want to protect their discoveries. Although much of the findings of professional motorsports shift techniques are generally kept under wraps as trade secrets, there are some items of general knowledge that are known about their methods. F1 shifting is currently performed using some sort of automated system, that still uses the driver to indicate when the shift takes place [8]. This can be either an up or down shift, but the driver is still the controlling element as to when, but not how the shift takes place. With regards to how the shift takes place, the sequence of operations that the computer goes through to actually perform the shifts is not publicized knowledge.

2.5 MPC 555 Microcontroller

The controller that will be used to implement the final control algorithm is the MPC 555. This is a reasonably priced Single Board Computer that includes a 32-bit PowerPC processor with a very small size [2]. It allows control algorthms to be written in `Simulink` and then loaded onto the controller. The controller includes two full 2.0B CAN communication devices, and 16-channel A/D converters with 10-bit resolution [2]. Additionally, this controller has been widely used at the Center for Automotive Research (CAR) here at Ohio State, so there is widespread knowledge about applied use of it.

2.6 Hewland NLT Transmission

Another important part of understanding how the shift control will work is to understand the functionality of the transmission that will actually be shifting. For the Buckeye Bullet 2, the Hewland NLT has been selected because it integrates the transmission and final drive into a single, compact package. The actual package is shown in Figure 2.3. Because it is a custom gearbox, a very large number of ratios can be chosen to construct the transmission, with a total of six ratios in the vehicle at a given time. A table of the ratios that have been selected are shown in Table 2.1, and the resulting speeds plotted in Table 2.5. These values were selected about a nominal shift point of 9500 RPM, and can be changed later if needed.

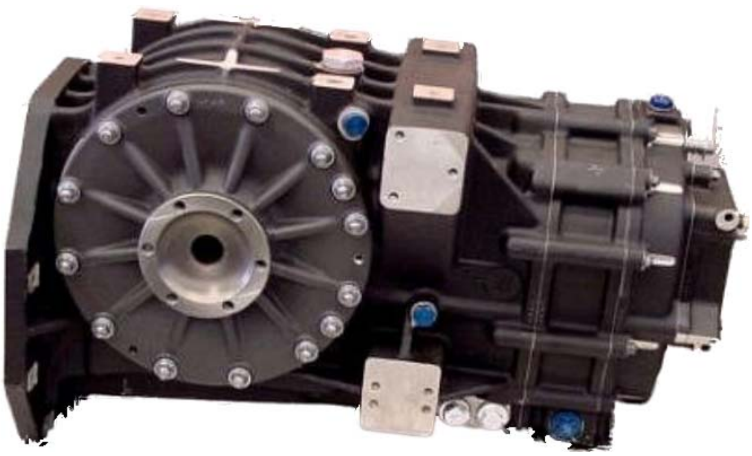

Figure 2.3: The Buckeye Bullet 2 Hewland NLT 6 Speed Transmission

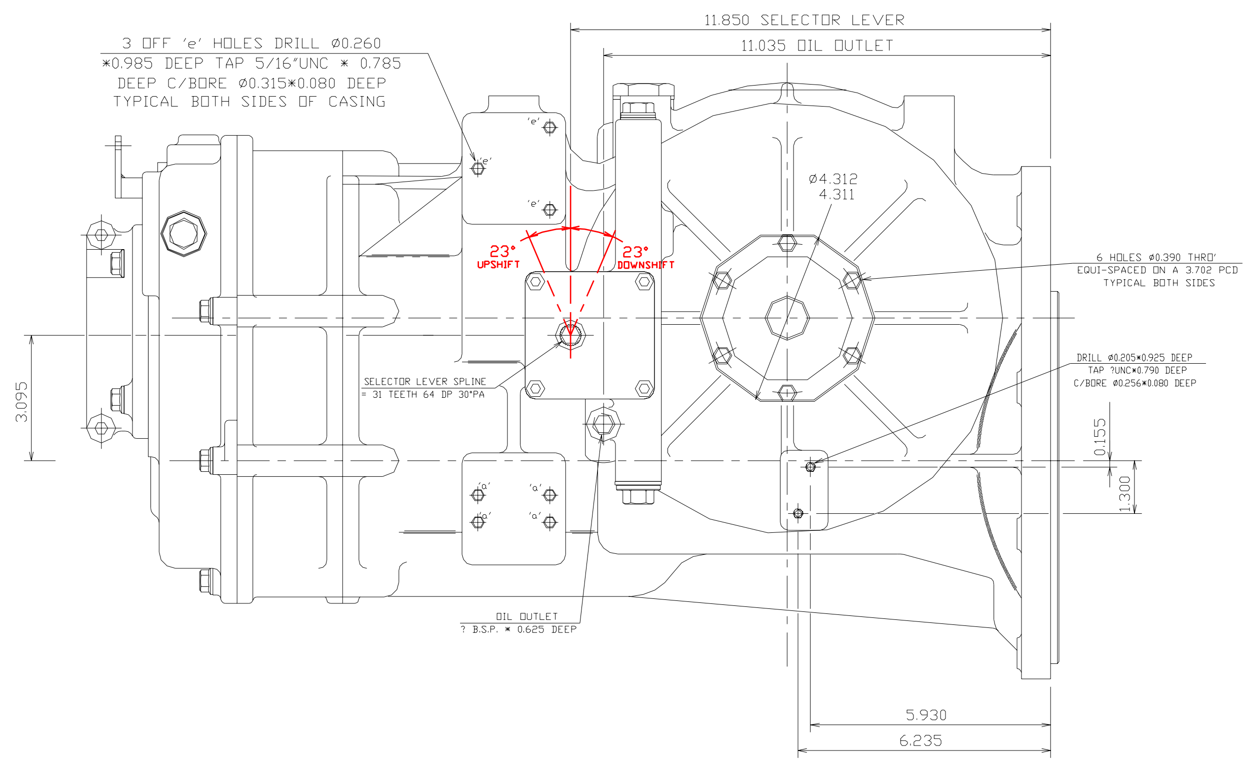

Figure 2.4: Hewland NLT Side View of Shift Input [1]

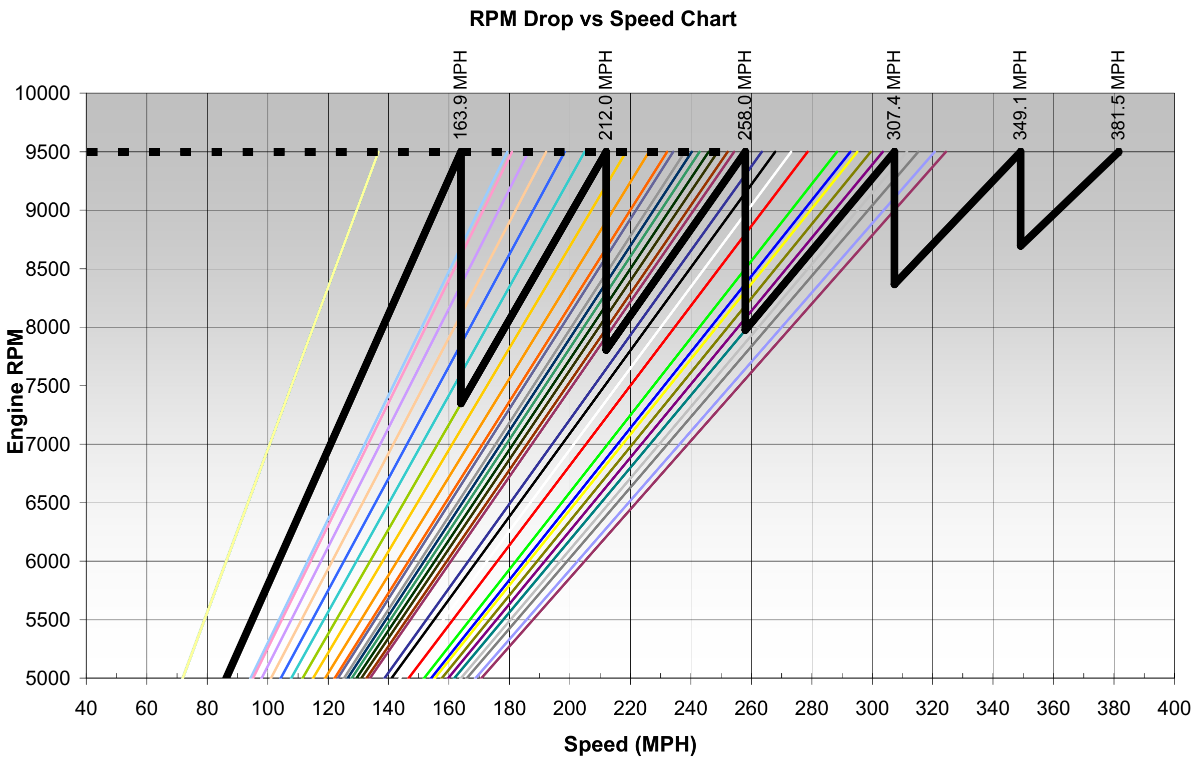

Figure 2.5: Transmission Gear Selection

Table 2.1: Buckeye Bullet 2 Hewland NLT Gear Ratios

Gear	Teeth Ratio	Ratio
1	14:35	2.500
2	15:29	1.933
3	17:27	1.588
4	18:24	1.333
5	23:27	1.174
6	27:29	1.074
Final Drive	10:18	1.800

2.7 Summary

A long history of research has gone into transmission control, but much of it has been applied to automatic transmissions. There has also been a fair amount of work to put more control of automatic transmissions into the hands of drivers who desire it. Electric powered record speed vehicles are custom built, and there have been minimal studies into how these cars can best utilize transmission optimization to maximize their power output.

Chapter 3

Methodology

3.1 Overview

This chapter describes the steps that will be taken to develop the new control scheme for the transmission in the Buckeye Bullet 2. Beginning with a model that has been both empirically and mathematically verified on the Buckeye Bullet 1, the effect of including a controller on the shift timing and consistency. This is a natural step, since the model for the Buckeye Bullet 2 is based upon this model, with certain parameters updated for the new design. The next step is to put a basic controller on the Buckeye Bullet 2 simulator. Once the controller is operating the transmission in an expected, stable manner, then the control scheme can be updated to a more sophisticated style, until a stable system is on the vehicle that maximizes the power output to the wheels.

3.2 Buckeye Bullet 1 Simulations

The Buckeye Bullet 1 was a very successful vehicle, largely because the early designs were done by very talented individuals. But before moving onto the future, we must first learn from our past. The Buckeye Bullet 1 simulator, shown in Figure 3.1, was started before the vehicle was in existance. It was vastly improved utilizing empirical data that was recorded on the Bonneville Salt Flats in 2003 and 2004. The shift timing design was built into this model in order to see the effect of the timing of the shift on the exit speed of the vehicle.

3.3 Buckeye Bullet 2 Simulations

Once a repeatable, reliable simulator had been built around the Buckeye Bullet 1, the various design changes were made to it to make simulations for the new vehicle. Items such as the aerodynamic coefficients, gear ratios, and other parameters were updated to reflect the new design. The top-level layout of the simulator can be seen in Figure 3.2. This simulator incorporates the power delivery from fuel source to fuel cell to power inverter to the electric motor to clutch to the transmission and finally to the wheels. This information is used in conjunction with the vehicle dynamics and

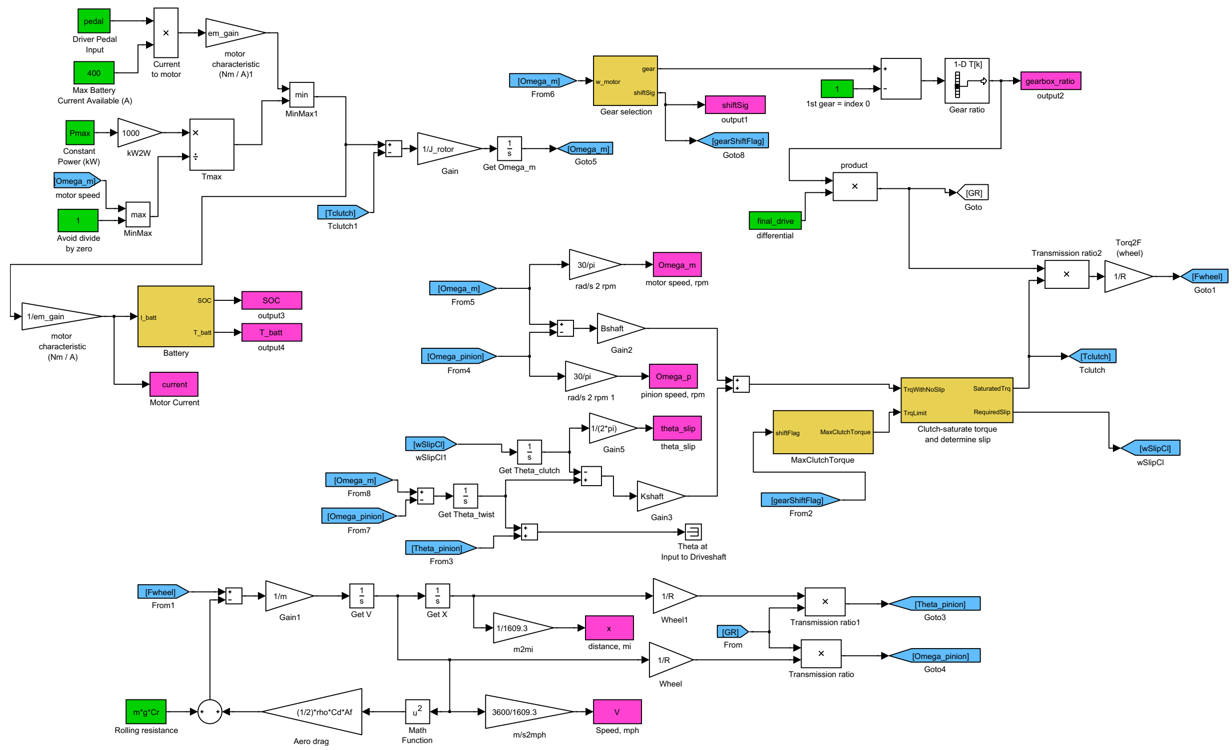

Figure 3.1: Buckeye Bullet 1 Simulator

traction information to simulate the position and speed information of the vehicle when driven in a particular manner.

This research focuses on the transmission portion of the simulator, which is broken down further in Figure 3.3. This block calculates the gear selection and final ratios, to be sent to the vehicle dynamics block to determine acceleration of the vehicle. In particular, this research is concerned with controlling the "Gear Selection" block in this diagram, which is further broken down in Figure 3.4. The setup shown here allows for a different shifting point to be set for each gear change in the simulation.

3.3.1 Assumptions

The Buckeye Bullet 2 is a very specialized vehicle. Its primary to set a land speed record. This means that it is designed to drive in a straight line at maximum power for at least 5 miles. Because of this, there assumptions related to the transmission that have been made in order to design the control scheme. They include:

- Vehicle downshift control optimization is not necessary
- Driver demands maximum available power from the vehicle during a speed run
- A robust transmission that can tolerate an automatic shift sequence is being used

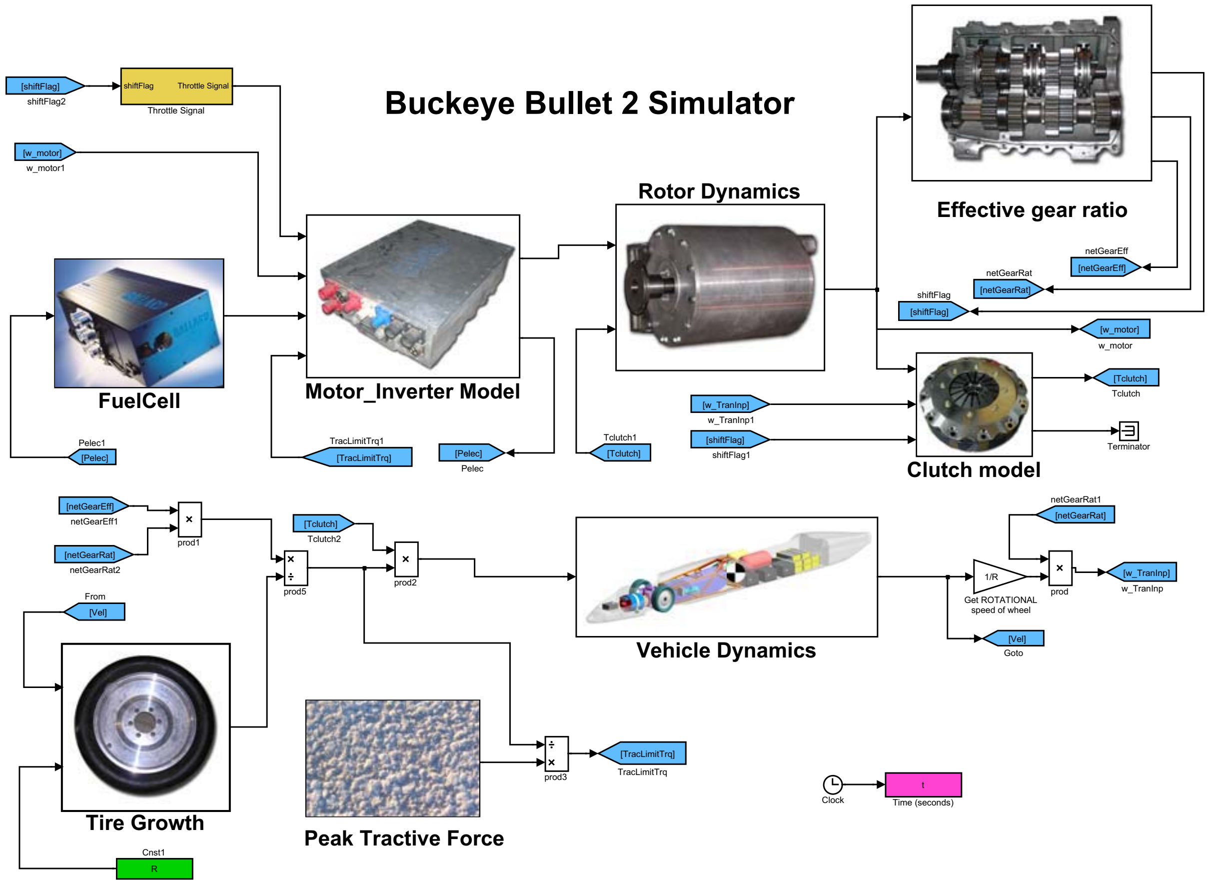

Figure 3.2: Buckeye Bullet 2 Simulator

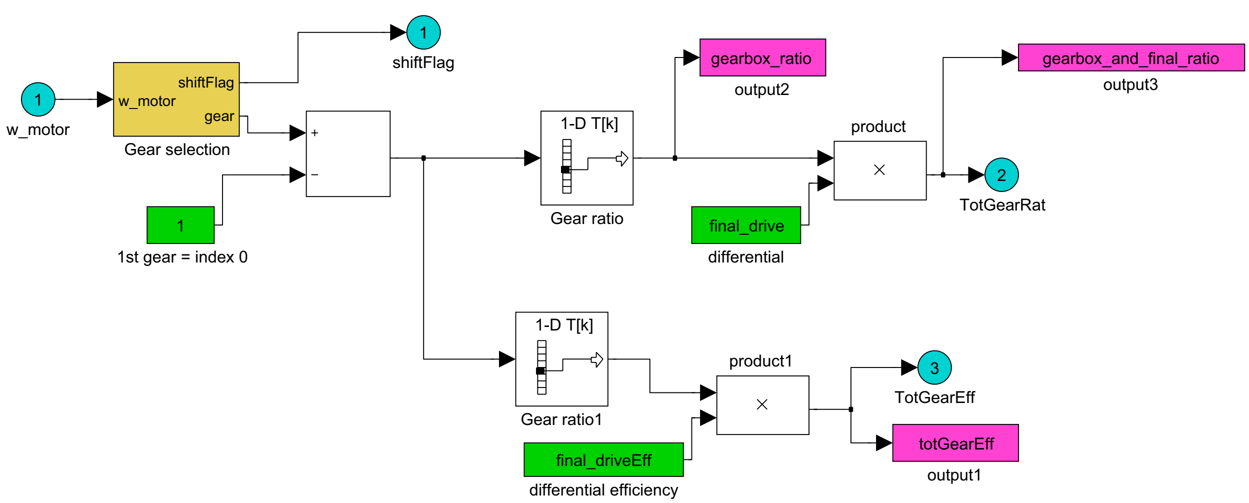

Figure 3.3: Buckeye Bullet 2 Simulator: Effective Gear Ratio

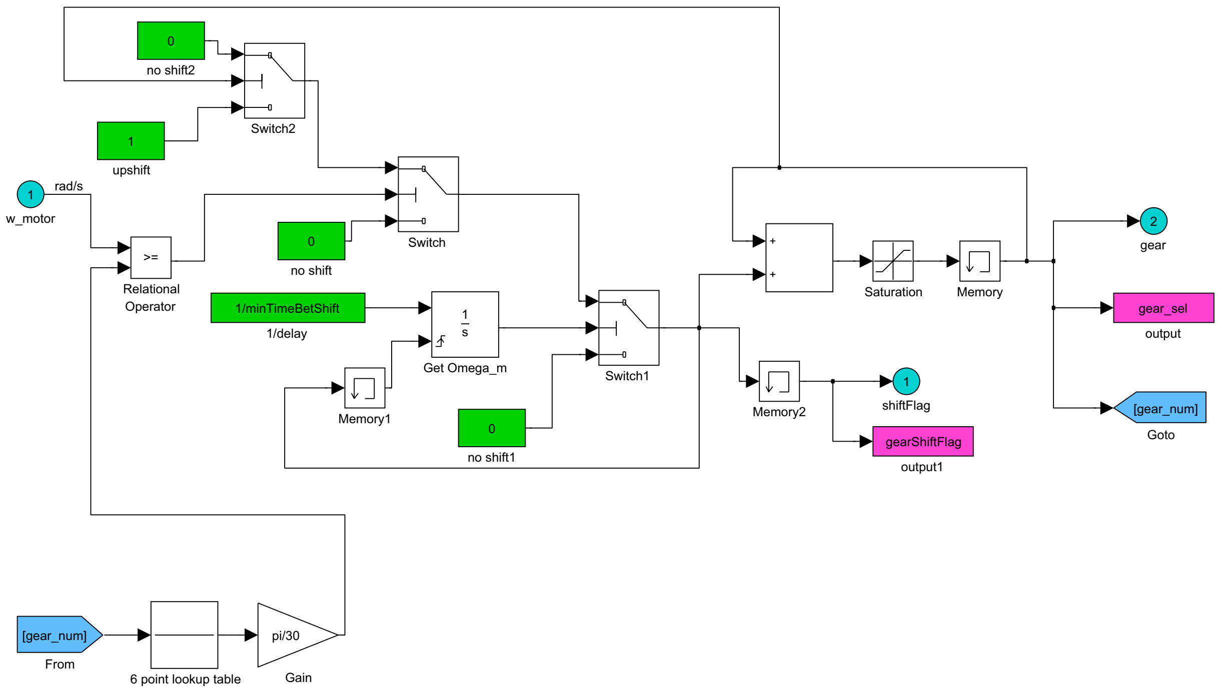

Figure 3.4: Buckeye Bullet 2 Simulator: Effective Gear Ratio: Gear Selection

3.4 Shift Sequence

Although the control of the shifting takes place by giving a computer controlled shift command, the timing of the actual sequence is important to understand. Figure 3.5 shows the strategy that will be used to implement the computer-actuated shifting. It begins with a shift signal, which comes from the computer. During time region 1, the clutch pressure is increased, until the motor is mechanically disconnected from the rest of the drive system. Then, during region 2, the shift solenoid moves the transmission into the next gear, and the motor uses regenerative braking, through the inverter to a dump resistor, to match the motor speed to the next gear. Finally, in region 3, the clutch is re-engaged, and the motor is connected to the driveline, and the shift is complete. As the system is advanced further, the overlap between the motor decelerating and the clutch engaging may be increased, allowing the clutch to absorb some energy of the motor to speed up the timing of the shift.

3.5 Summary

This chapter has explained the strategies used to develop a method of transmission control on the Buckeye Bullet 2. Through simulations, the results of various control schemes are explored and discussed. The principal design tool is a simulator capable of predicting the vehicle response in the face of changes in transmission shift logic and timing. The following chapters will make use of this simulator as a tool for analysis of the various control methods.

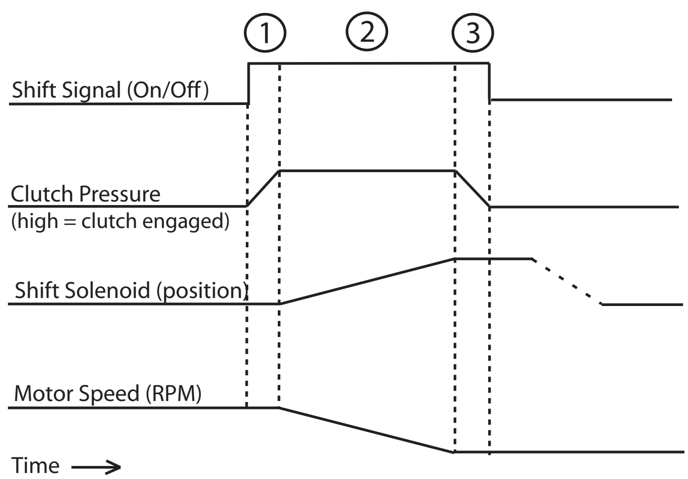

Figure 3.5: Shift Sequence

Chapter 4

Analysis and Results

4.1 Introduction

This chapter explores various control methods that could potentially be used on the Buckeye Bullet 2. It will explore the simulation of shift timing on the Buckeye Bullet 1, look at how the electric drive motor delivers power, and finally, how the shift points can be chosen to maximize the vehicle power output.

4.2 Buckeye Bullet 1 Simulation Results

As explained previously, the Buckeye Bullet 1 simulator was able to predict what happened on the track with a high degree of accuracy, with data collected by a datalogger and Global Positioning System (GPS) data. This data was used to update the simulator, and eventually allow it to more accurately predict the performance of the vehicle.

4.2.1 Statistical Shift Analysis

Using data from the Bonneville Salt Flats in August 2004 and October 2004, the shift time duration was analyzed, as can be seen in Table 4.1. The data showed that the shift duration, as manually performed by Roger Schroer(see Section 1.2.3), was between 0.5 to 1.4 seconds, averaging 0.836 seconds, with a standard deviation of 0.312 seconds. When the vehicle is traveling at nearly 300 mph, this is a significant amount of time and distance where the speed is not increasing due to no motor power to be applied, over 600 feet for the 1.4 second shift. During this time, rolling and aerodynamic resistance work to slow the vehicle.

The shift points, as measured in RPM, were also analyzed. Table 4.2 shows the shift points performed by Roger Schroer in the Buckeye Bullet 1. He was instructed by the team to shift at 9500 RPM. According to the data collected in Table 4.2, his shifts ranged from 9100 to 9974 RPM, and had an average of 9539 RPM and standard deviation of 219 RPM.

Table 4.1: Roger Schroer's Shift Times (in seconds)

Gear Change	$1 \rightarrow 2$	$2 \rightarrow 3$	$3 \rightarrow 4$	$4 \rightarrow 5$
International Record Run 1	1.4	0.9	0.9	N/A
International Record Run 2	1.2	1.0	1.4	N/A
U.S. Record Run 1	0.7	0.6	0.5	0.55
U.S. Record Run 2	0.8	0.6	0.55	0.6

Table 4.2: Roger Schroer's Shift Points (in RPM)

Gear Change	$1 \rightarrow 2$	$2 \rightarrow 3$	$3 \rightarrow 4$	$4 \rightarrow 5$
International Record Run 1	9740	9326	9630	N/A
International Record Run 2	9114	9309	9510	N/A
U.S. Record Run 1	9742	9974	9550	9452
U.S. Record Run 2	9711	9580	9530	9384

4.2.2 Simulation of Shortened Shift

The first step towards improving exit speed via shift control is analyzing the effect of shift time on the Buckeye Bullet 1 simulator. Previously, the simulator used a constant shift time in its simulation. The box plot of the data from Table 4.1 is overlaid on top of the simulation results for shift timing in Figure 4.1. This figure shows that a gain of approximately 6 mph in exit speed is potentially achieved simply by reducing the shift time. The box plot also illustrates that there is high degree variability in the driver's shift time. Combined together, an automated shift system could potentially improve vehicle exit speed, as well as increasing the consistensy from run to run. If the driver is no longer focused on the tachometer and watching when to shift, he can more safely pilot the vehicle down the course.

4.3 Shift Solenoid

A single linear solenoid was chosen to physically perform the shift operation on the transmission. Because the transmission is sequential, a simple push-pull solenoid is needed, as opposed to a more complicated H-pattern layout. Figure 4.2 shows the solenoid that has been selected. This particular solenoid is capable of supplying 50 lbs of force, weighs just 3.3 pounds, and has a 2 inch range of travel.

This particular solenoid was tested to check the range of travel, to see if the simulated effects of a quicker shift might be possible. Figure 4.3 shows the solenoid's distance of travel versus time, bench tested under no-load conditions. An accelerometer was attached to the end of the solenoid, and integrated twice to determine the position of the end of the solenoid. Both the shift signal and the accelerometer were recorded using an oscilloscope with a 10kHz sample rate. According to

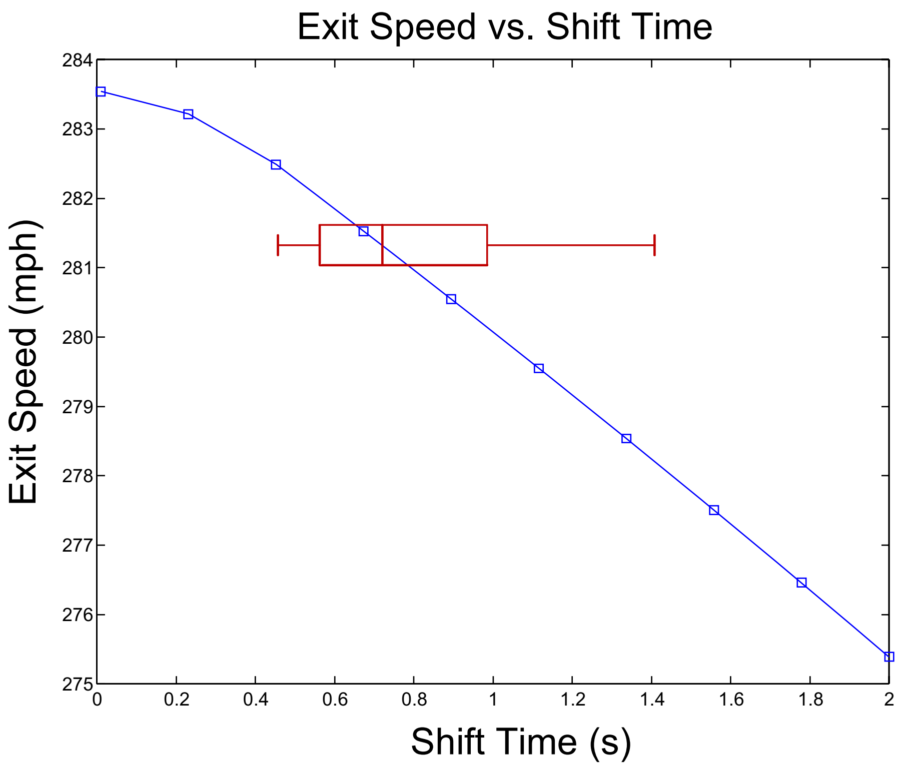

Figure 4.1: Buckeye Bullet 1 Shift Timing

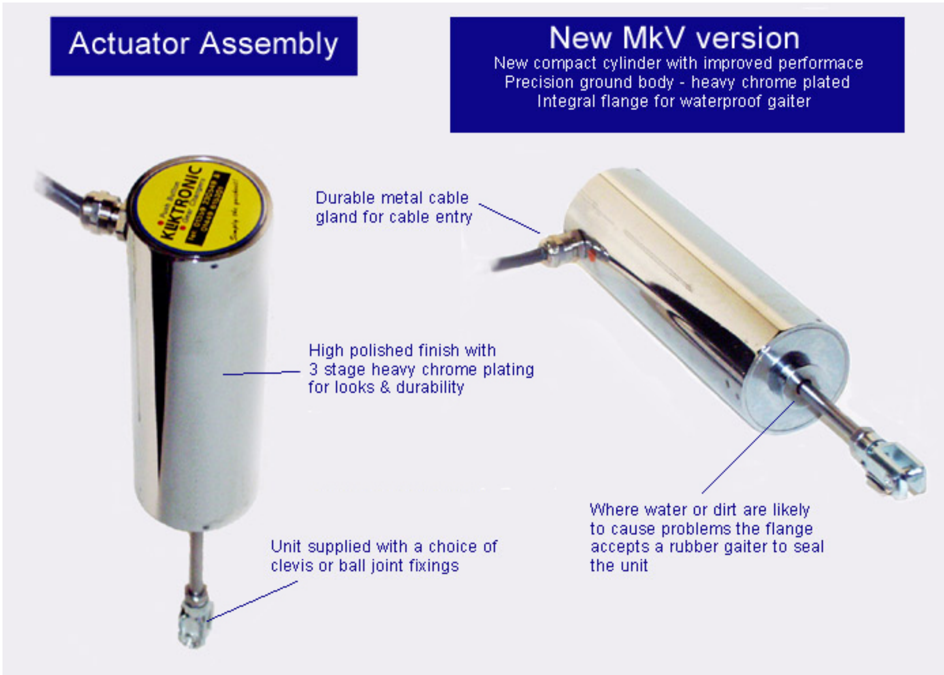

Figure 4.2: Kliktronic Gear Changer [4]

this test, it took approximately 50 ms for the lever to move, and 8 ms for the mechanical relays to provide power to the solenoid. By replacing the mechanical relays with solid state relays, the 8 ms delay might be nearly eliminated .

4.4 Buckeye Bullet 2 Simulation

The Buckeye Bullet 2 is currently still under construction, and the Buckeye Bullet 1 no longer runs, since it has been retired. Therefore, the most logical method of testing and comparing the control strategies is by implementing them into the simulator. There are a few advantages to this approach. First, the simulator can be adjusted and tweaked quickly to obtain results in a matter of seconds, whereas full on-vehicle testing could take days to obtain true results. Secondly, the MPC555 microcontroller can be programmed in `Simulink`, which is the native environment for the simulator. This allows blocks to be placed in the simulator and moved to the controller, only needing the inputs and outputs to be connected in the software.

4.4.1 Development of Control Scheme

The system as it currently exists is a driver monitoring a tachometer and shifting at a given setpoint. Once this is understood, the next step is to develop a control scheme that will control the shift points. The idea here is that a computer controlled shift system can react more quickly and analyze more information than a preoccupied driver can. The next step is to look at several of those control

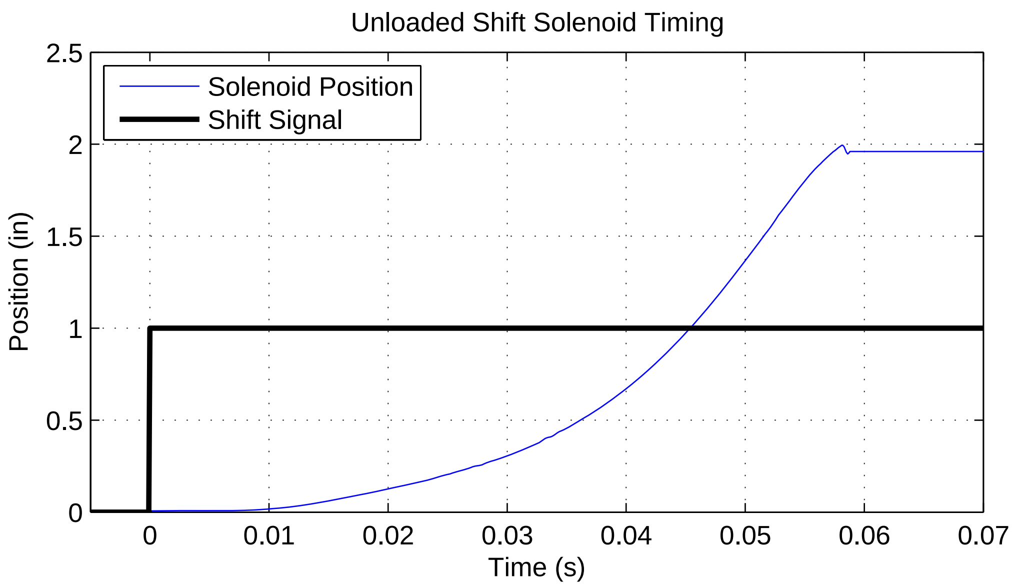

Figure 4.3: Shifting Solenoid Test

methods, and study them to see which yield the best results while still keeping complexity low and reliability high.

4.5 Constant Shift Point

The first method to be analyzed is taken directly from the ideal Buckeye Bullet 1 control. The driver was instructed to shift at a certain RPM, so in this control method, the computer will shift at a set RPM. This is a basic single input, single output (SISO) system in which the output shift signal is based exclusively on the motor RPM.

To demonstrate the results of two different setups with a static shift point, two fuel cell membranes are looked at: MEA9 and MEA4B. These membranes are being used for this study because they will both eventually be used on the Buckeye Bullet 2. For these purposes, it is just important to understand that they have different Current vs. Voltage characteristics, and that the MEA9 is the newer of the two membranes. For the purpose of this study, it is also not necessary to understand the operation of the fuel cell, such as how the membrane works, but rather just recognize that these are two sources of power that will operate differently in the vehicle.

Figure 4.4 shows the result of different shift points with the exit speed of the vehicle using the MEA4B membrane. This plot illustrates that the maximum exit speed is achieved when the shift point is set to 7795.9 RPM, and that exit speed penalties become significant when the shift point is off by more than 1000 RPM. Figure 4.5 shows the result of running the vehicle with the optimized shift point. Looking at the plot of motor power vs. distance in Figure 4.5, it can be seen that the shift sometimes goes from a higher power to lower power, and vice versa. Next, the

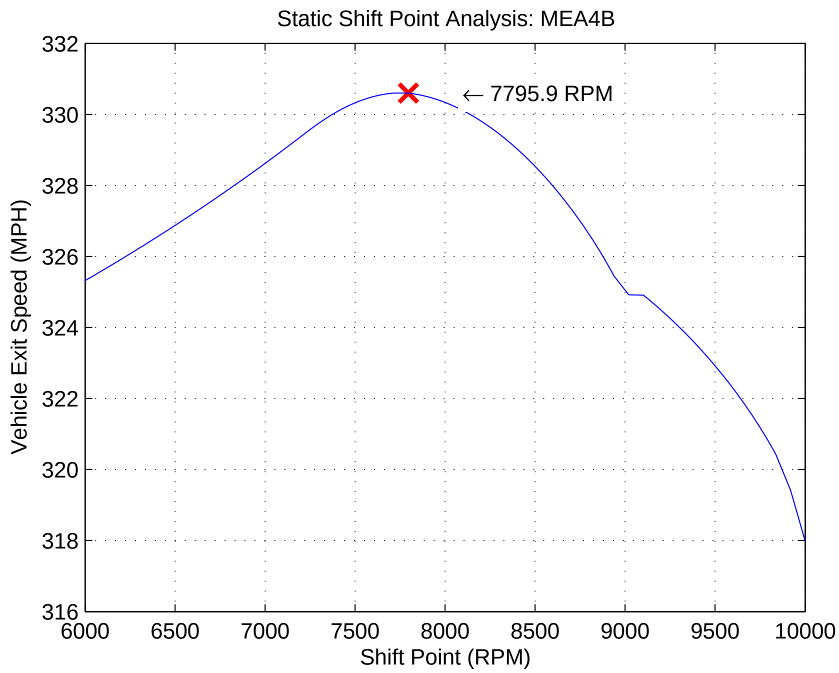

Figure 4.4: Static Shift Optimization with MEA4B Membrane

MEA9 membrane was optimized, seen in Figure 4.6, which gives an optimal shift point of 8449.0 RPM. This membrane is less forgiving to errors in shift point than the MEA4B membrane, due to the narrow optimization peak in Figure 4.6. Figure 4.7 shows the corresponding run with the optimized shift point, and has similar characteristics as the MEA4B membrane. As an interesting note, if the shift point for the MEA4B membrane were used with the MEA9 membrane, the exit speed would be nearly 6 mph less than in the optimized case.

4.6 Motor Mapping

In September 2006, the Buckeye Bullet team tested the three-phase electric motor to an electric motor dynamometer in Pennsylvania. In the setup, the motor was geared down to match the maximum speed on the dynamometer motor, and the Buckeye Bullet motor was able to be run up to the maximum power. This can be seen in Figure 4.8. Through this testing, a motor "map" was able to be generated, which gives the power versus D.C. input voltage and motor RPM. The resulting map is shown in Figure 4.9. In this map, a line of maximum power can be seen. This means that for a given voltage, there is a point in which the motor is able to output the maximum power. Ideally, the precise gear ratio would be chosen to stay at the maximum power range, as might be possible with a continuously variable transmission (CVT), but since the transmission that is being used in the Buckeye Bullet 2 has a set number of gears with set ratios, this is not possible. For the power ranges that this vehicle deals with, a CVT would not be practical. Additionally, the

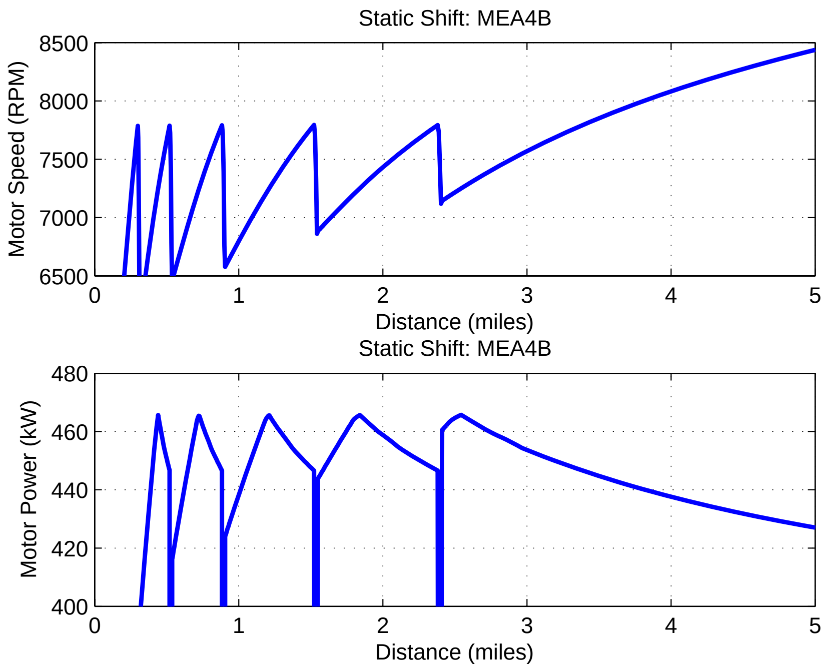

Figure 4.5: Optimized Static Shift with MEA4B Membrane

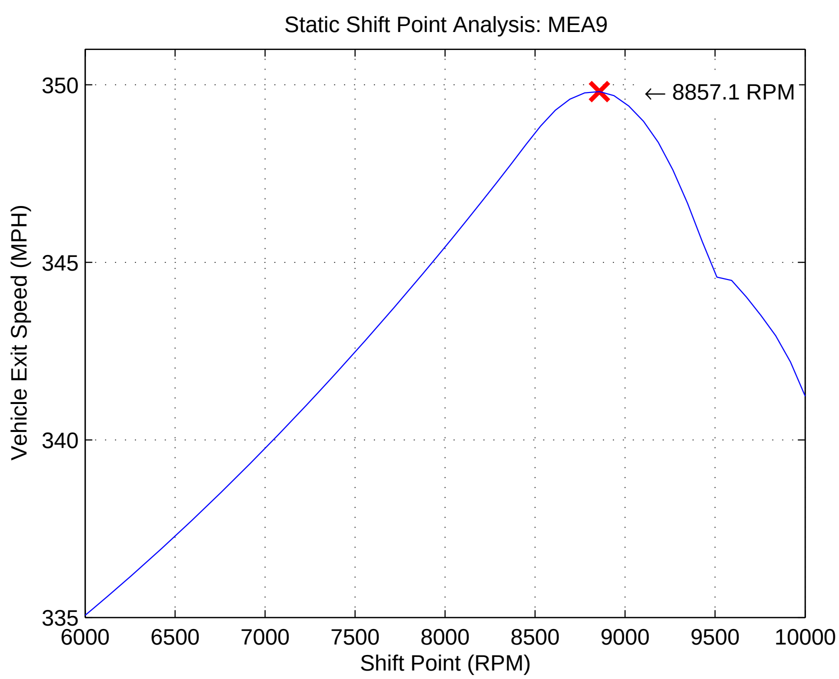

Figure 4.6: Static Shift Optimization with MEA9 Membrane

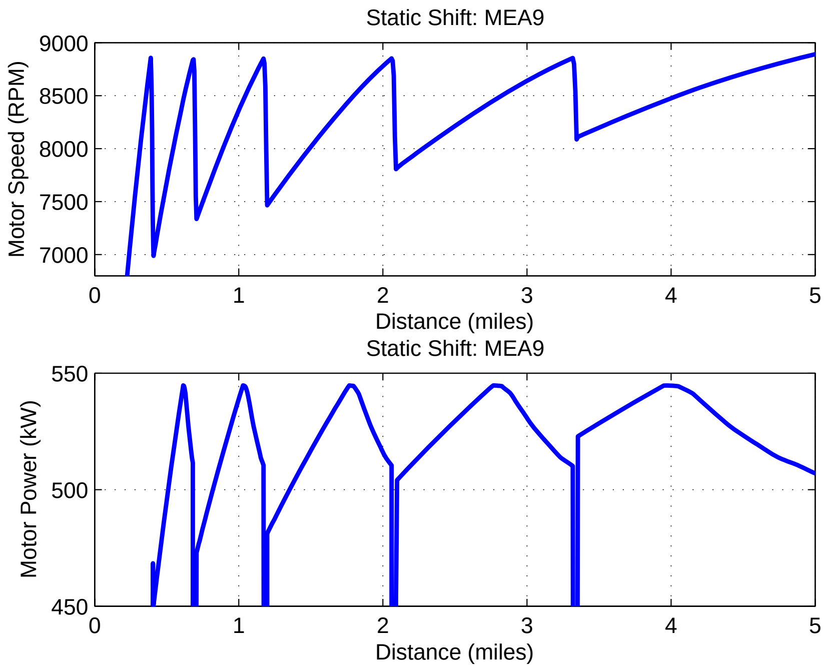

Figure 4.7: Optimized Static Shift with MEA9 Membrane

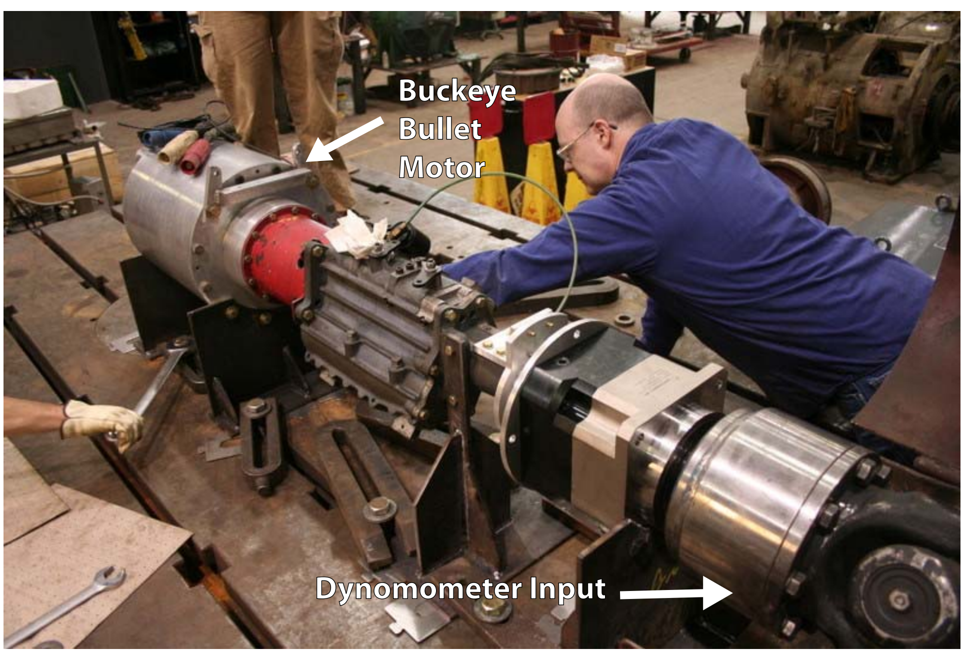

Figure 4.8: Testing the Buckeye Bullet Motor

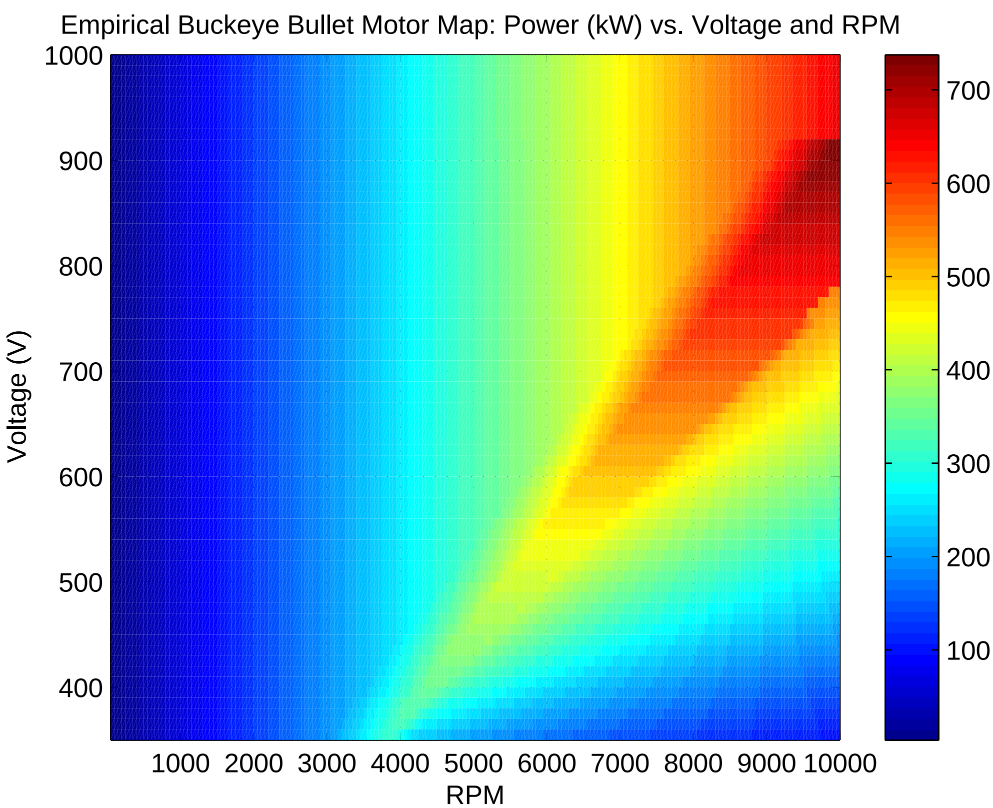

Figure 4.9: Buckeye Bullet Motor Map

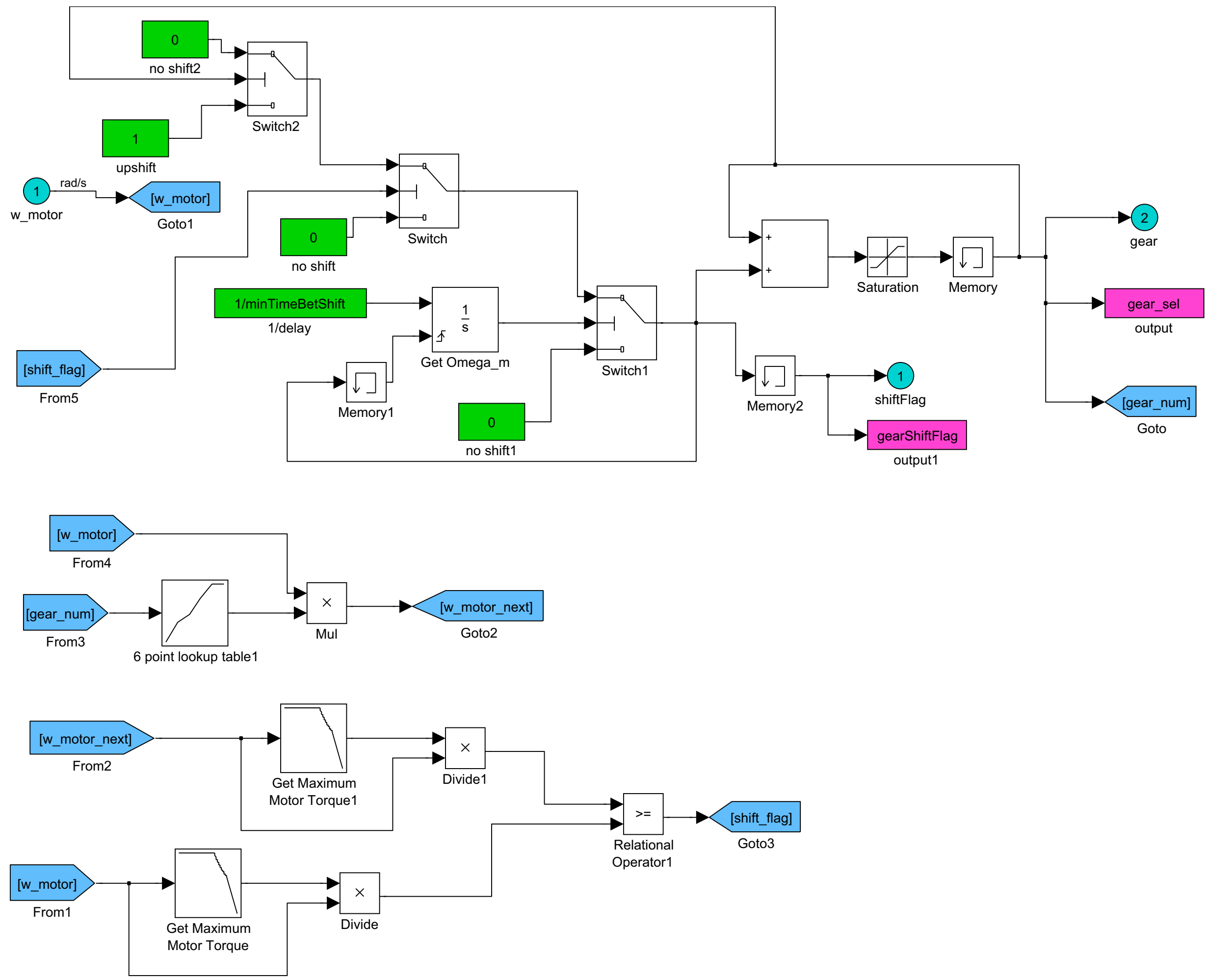

Figure 4.10: Power Tracking in Simulator

lower efficiency of the CVT is not desirable.

4.7 Tracking Shift Point

Using the information gained from testing the power in the motor, it might be possible to maximize its power output. This leads to a power-tracking shift point, the next control strategy.

The power-tracking shift point control strategy uses the knowledge of the current power of the motor, and the potential power if the shift were performed. If the potential power is greater, then a shift should take place. This potential power is determined using the map generated in Figure 4.9, using voltage and motor RPM as inputs. The implementation of this strategy is shown in Figure 4.10. It utilizes a lookup to the motor map from Figure 4.9 to determine whether or not an upshift should take place. Using the MEA4B membrane, this method is demonstrated in Figure 4.11. It can be seen in the lower plot that the transmission is being shifted when the power in the next gear

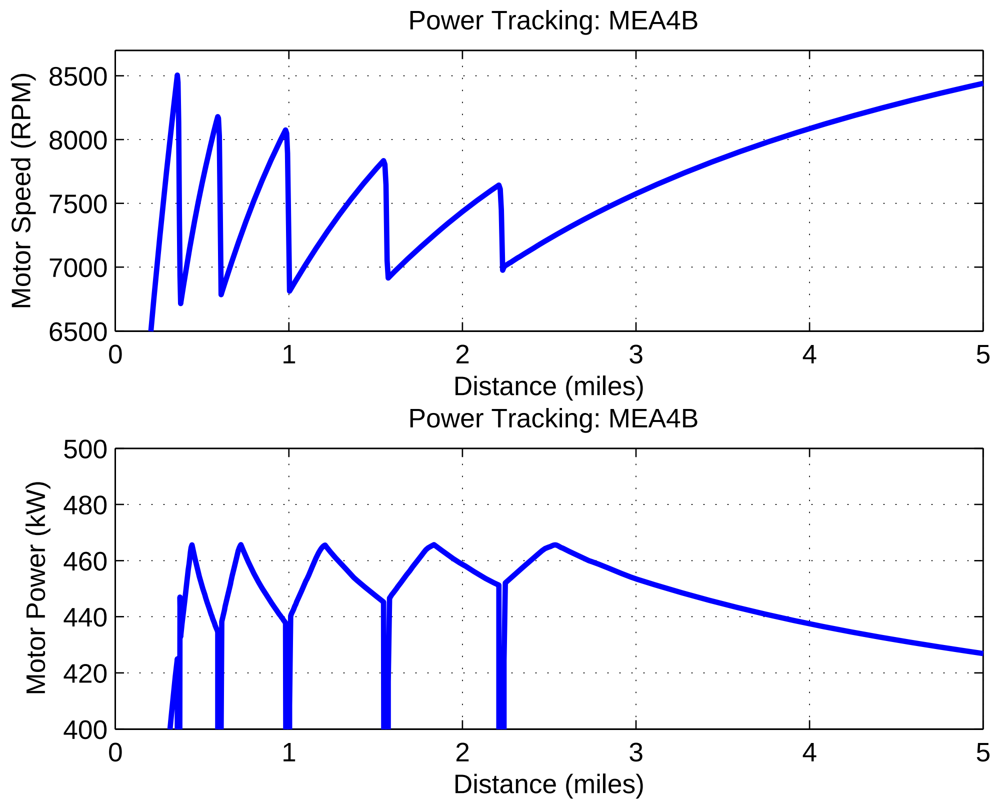

Figure 4.11: Power Tracking on the MEA4B Membrane

gives a greater power from the motor. Regardless of how much power is generated by the motor, there will be a certain amount of rolling and aerodynamic resistance. But, the greater the power that can be generated by the motor, the greater than can be contributed to overcoming the inertial forces, and thus increasing the vehicle speed.

One interesting result that should be noted is that in Figure 4.11, the shifts occur relatively early, which puts them at a time when the vehicle is traveling slower, and thus at a time when there is less aerodynamic resistance. This will cause the drop in speed during the shift to be decreased, and help increase the exit speed.

4.8 Summary

Several control strategies have been proposed to increase vehicle exit speed. Table 4.3 explains the two control strategies, and the resulting top speeds. For each of the membranes, the change from static shift point to power tracking did not seem to increase the top speed by much. In fact, the increase was merely 0.122 MPH for the MEA4B membrane, and 0.144 MPH for the MEA9 membrane.

But what if things are changed in the vehicle that cause the optimized point to be changed,

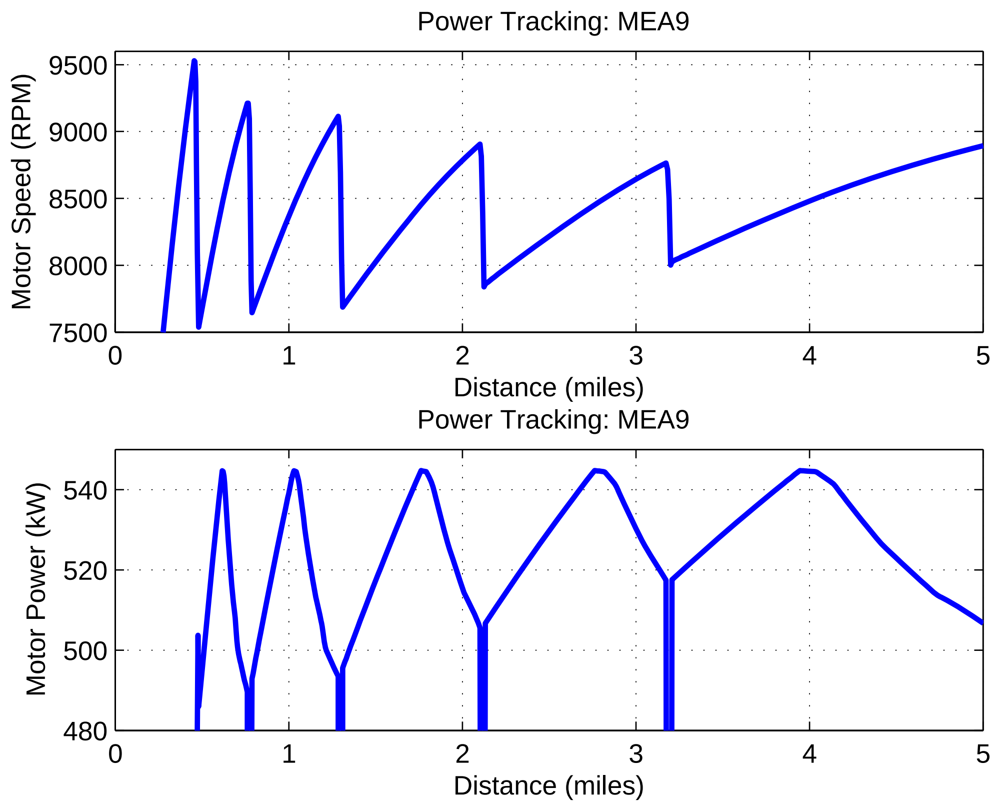

Figure 4.12: Power Tracking on the MEA9 Membrane

in the same way that it changed in Figures 4.4 and 4.6? It has already been established that, even if it just mimics the operation that was being done by the driver before, the transmission control system is a valuable system in the vehicle. It increases safety, reliability, and consistency, and utilizes the vehicle controller that is already present in the vehicle. But if parameters such as characteristics of the fuel cell or inverter settings are changed, is it necessary to go in and change the shift point , whether it be using the static or power tracking methods? With the static method, if any parameter is changed, the shift point must be changed to get the peak power output, and thus peak speed. With so much team activity going on when the vehicle runs, this is another element to be considered and changed. But, if the shift point could be eliminated as a team consideration, and just trusted to the control system, then it would be one less thing to take care of when testing or performing speed runs. With the power tracking method, shift points are automatically adjusted and optimized. It is a robust method that adjusts to the current state of the power source, so it can be used whether or not the power source is changed or updated.

Table 4.3: Summary of Control Strategy Results

		Shift Point (RPM)					
Membrane	Control Type	$1 \rightarrow 2$	$2 \rightarrow 3$	$3 \rightarrow 4$	$4 \rightarrow 5$	$5 \rightarrow 6$	Exit Speed
MEA4B	Static Shift	7795.9					330.601
MEA4B	Power Tracking	8518.7	8179.7	8084.8	7841.5	7648.7	330.723
MEA9	Static Shift	8857.1					349.807
MEA9	Power Tracking	9529.2	9211.5	9113.3	8905.3	8765.0	349.951

Chapter 5

Conclusions and Recommendations

5.1 Summary of Results

When the static shift point is properly set, there is not much of a gain by using the power tracking method of control. But, since the power tracking method can adjust based on the power source, it is a more desirable method because it can be left to operate the transmission upshifts without having to change the shift point when a parameter on the vehicle changes.

5.1.1 A Broader Scope

While the algorithm that was developed for this research may apply to a very narrow definition of vehicles, namely electric land speed vehicles, the strategies generated can be extended to a much broader field of applications. The algorithm for the Buckeye Bullet 2 uses the specific Power vs. Speed curve for its electric motor, shown in Figure 4.9, to maximize power output through shifting times. However, by simply exchanging the maximization of power for the maximization of say, efficiency, the algorithm suddenly becomes adapted to shift in order to maximize the efficiency of a vehicle. Extend this to common street automobiles, and include the efficiencies of the entire driveline, and the algorithm will shift at points which will maximize the efficiency of the car. This might enable it to have a longer range, better fuel economy, or extend the life of various components. Combined with hysteresis, it can be extended to a downshift to allow for control of consumer vehicles.

In general, the use of a microcontroller in the vehicle's data network could eliminate the automatic transmission, to be replaced by an actuated manual transmission. To the driver, the change is transparent, and shifting occurs automatically as it would have before. It makes the implementation of a manumatic system even easier, by adding a few more inputs to the controller, and including them in the algorithm. The system reduces transmission complexity, which in turn will reduce costs, and chance for breakdown.

5.2 Recommendations

Once a working vehicle is ready, this system is suggested to be one of the first advanced systems implemented. It removes much of the variability within a run, improves safety, and in the end, gives a higher exit speed, and thus a potentially higher speed record.

5.2.1 Future Work

The next stage of this transmission control is to implement the `Simulink` code onto the MPC 555 controller, and install it onto the Buckeye Bullet 2. From there, the control strategy can be further developed to become more intelligent, based on other vehicle parameters that might be important to the shift point. Using an idea the automotive industry has termed "sensor fusion," data from anywhere on the vehicle can be pulled to help make the decision about whether or not to shift. If a temperature sensor on the transmission indicates that performing a shift might be harmful to the transmission, then the shift will not take place, and the driver will be notified.

5.3 Conclusion

This research showed that it would be possible to maximize the power output of the motor using a controller to choose the shift points. With a controller already in the vehicle, and a clear benefit seen in having the transmission automated for areas of safety and consistency, this research showed that it is beneficial to include this type of control on the Buckeye Bullet 2.

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